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Title: Retrieval of high-resolution kinematic source parameters for large earthquakes

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Abstract

We have extended a method for Finite Fault Inversion based on a least square inversion of seismic waveform data to include other phases than body waves such as surface waves and normal modes. Although initially intended, and applied successfully, to serve as a natural regularization of the inversion process, we have found that the addition of long period surface waves is also very advantageous for the inversion of very large earthquakes where the source time exceeds the arrival window of the direct P and S waves. This allowed us to study the source process of the devastating 2004 Andaman-Aceh earthquake and tsunami and its largest aftershock.

1 Introduction

The inversion of seismic data for kinematic rupture parameters is a very non-unique process, especially if only teleseismic data is available. This results in the need to regularize the inversion process using rather arbitrary a-priori assumptions regarding the end result, in terms of smoothness of rupture, rupture velocities, extent and complexity. Adding additional constraints from other types of data, such as geodetic, or local strong motion data can alleviate this problem to a certain extent while at the same time providing better physical constraints on the solution. Although initially counter-intuitive, we have found that including long period surface waves in the inversion process helps a great deal in stabilizing the inversion process by constraining the overall source parameters such as rupture extent and centroid of the moment release. This reduces the importance of artificial damping and smoothing operators while still allowing us to consider an extensive parameter space for the solution.

During the course of this project, the giant 2004 Sumatra earthquake and tsunami occurred, which brought an un-foreseen advantage of this approach to the foreground. With a total rupture duration of approximately 10 minutes, this event was too large to be studied in its entirety using teleseismic body waves because of interference of secondary phases such PP and SS later in the record. By using the long period surface waves, we were able to retrieve details of the rupture process, which were not obtainable using the traditional methods.

Because of the significance of the tsunami generated after the 2004 event, and the large contrast in size to the tsunami generated after the 2005 earthquake directly south of the 2004 event, we also simulated the tsunamis based on the results of our inversions for both events.

2 Method

2.1 Inversion

We propose to use the following technique to determine the temporal and spatial distribution of slip on the fault plane. Teleseismic body waves are inverted for fault slip using the multiple-time window algorithm of Thio et al. (2004), which is a modified form of the slip inversion method developed by Hartzell and Heaton (1983). This method involves the construction of the normal equations:

$$\begin{pmatrix} C_d^{-1}A \\ \lambda_1 S \\ \lambda_2 M \end{pmatrix} x = \begin{pmatrix} C_d^{-1}b \\ 0 \\ 0 \end{pmatrix}$$

The elements of matrix A consist of Green’s functions of seismic waves for body waves, calculated by using unit slip point sources at the center of each subfault, S is a matrix of smoothing constraints and M is a minimization criterion. λ_1 and λ_2 are hyper-parameters, which weigh the smoothing and minimization criteria, respectively, and are chosen by trial and error as the maximum weights that do not significantly degrade the fit to the observed waveforms. Finally, C_d is a data covariance matrix. Following Hartzell and Langer (1993) we use a diagonal matrix whose values are such that each trace in the vector b will have a peak value of 1.

A least squares inversion with positivity constraint is applied to the normal equations using the Householder reduction method of Lawson and Hanson (1974). As discussed by Hartzell and Langer (1993), among others, the positivity constraint is needed to prevent instability in the inversion, which may manifest itself in adjacent subfaults taking on equal but opposite slips. The rake angle of the slip is allowed to vary, however, within a range of 90 degrees.

The subfault underlying the epicenter determined by, for example, the USGS, is used as the starting point for rupture in the inversion. The maximum speed of rupture propagation is set to a fixed value, and each subfault is permitted to slip, with discrete time-steps, over a predefined duration after the passing of rupture front. The slip on each subfault at each step is parameterized with triangular source time with a half-duration equal to the time-step, allowing for some variation in rupture velocity. The time step and triangle half-width are chosen to match the frequency content of the observed P-waves. Further details of our implementation can be found in Thio et al. (2004), as well as Ammon et al.

(2005). The method is very flexible and can incorporate a wide variety of data including surface wave, geodetic and tsunami data.

2.2 Green's functions

The body wave Green's functions for the inversion were computed using a simple hybrid method that couples a propagator matrix element for local structure with a teleseismic ray tracing element, both of which use 1-D velocity models (Kikuchi and Kanamori, 1991). For the long period surface waves (60-300 sec) we used a traveling surface wave approximation coupled with the fundamental mode phase velocities adjusted using a global model of phase velocities (Ekström et al. 1997). We also added a separate set of very long period waves (300-1000 sec) using full normal mode calculations (Clévédé and Lognonné, 1996) separately. For these waves, no phase corrections were applied since the corrections at these periods are negligible.

2.3 Data

We used worldwide broad-band data provided by the IRIS Data Management Center and removed the instrument response to obtain the displacement data.

3 Results

3.1 Rupture models

In Figure 1a we show the rupture model for the 2004 Sumatra earthquake from the inversion long period surface waves. The slip distribution is almost uniquely uni-lateral with the rupture extending over a distance of 1000 km with a rupture duration (Figure 1b) of almost 10 minutes. The waveform fits (Figure 2) are very good. In contrast, the rupture distribution of the 2005 event is significantly smaller with the main slip distributed over a length of less than 300 km (Figure 3). When compared to the main event slip distribution, it is very clear that the March 2005 event ruptured a separate section of the subduction zone interface directly adjoining the 2004 rupture.

3.2 Tsunami simulation

Because of the severity of the tsunami following the 2004 earthquake (M_W=9.1), and in contrast, the relatively minor tsunami effects from the 2005 earthquake (M_W=8.7) we decided to use these rupture models to simulate the tsunami excitation and propagation in the region. In Figures 4 and 5 we present the simulation results for both events, and the large difference in size of the tsunami is immediately apparent. There are several reasons for this difference including the much smaller extent and slip of the rupture and the larger depth of the 2005 earthquake. The modeled tsunami heights for both events correspond well with the observed heights, suggesting that the inversion of long period surface waves is a very effective tool for the rapid determination of rupture extent, and in the case of submarine events, the tsunamigenic potential.

4 Conclusion

We have shown that the inclusion of long period surface waves not only results in better regularization of the finite fault rupture process, but also allows us to obtain rupture models for very large earthquakes where regular body wave methods fail due to the long duration of the rupture. This suggests that this method has great potential for the rapid determination of earthquake rupture extent, and thus the evaluation of damage potential from both shaking as well as tsunami.

5 References

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7 Figures

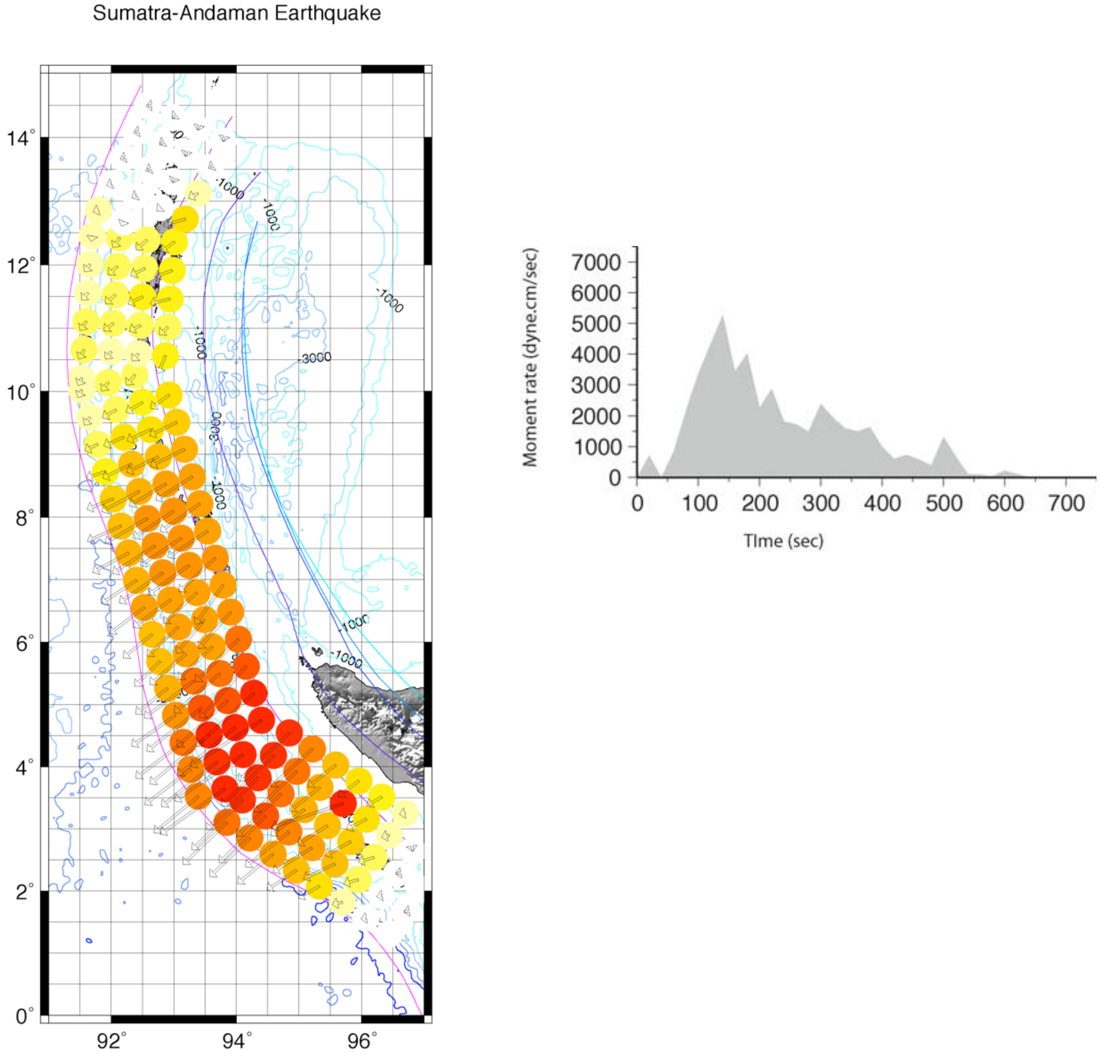

Figure 1. a (left) - Rupture model for the 2004 Sumatra earthquake from the inversion of long period surface waves. b (right) – Source time function for the 2004 event.

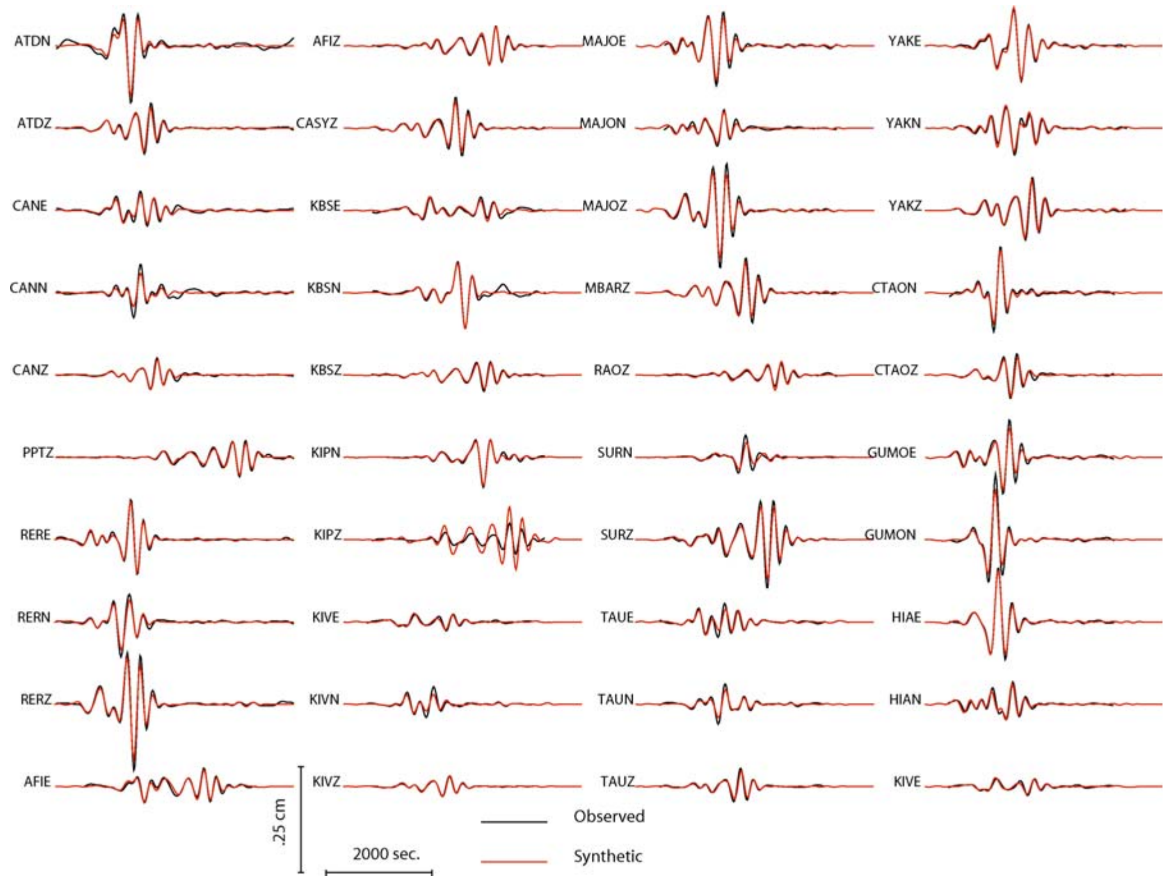

Figure 2. Observed and modeled long period surface waves for the rupture model in Figure 1.

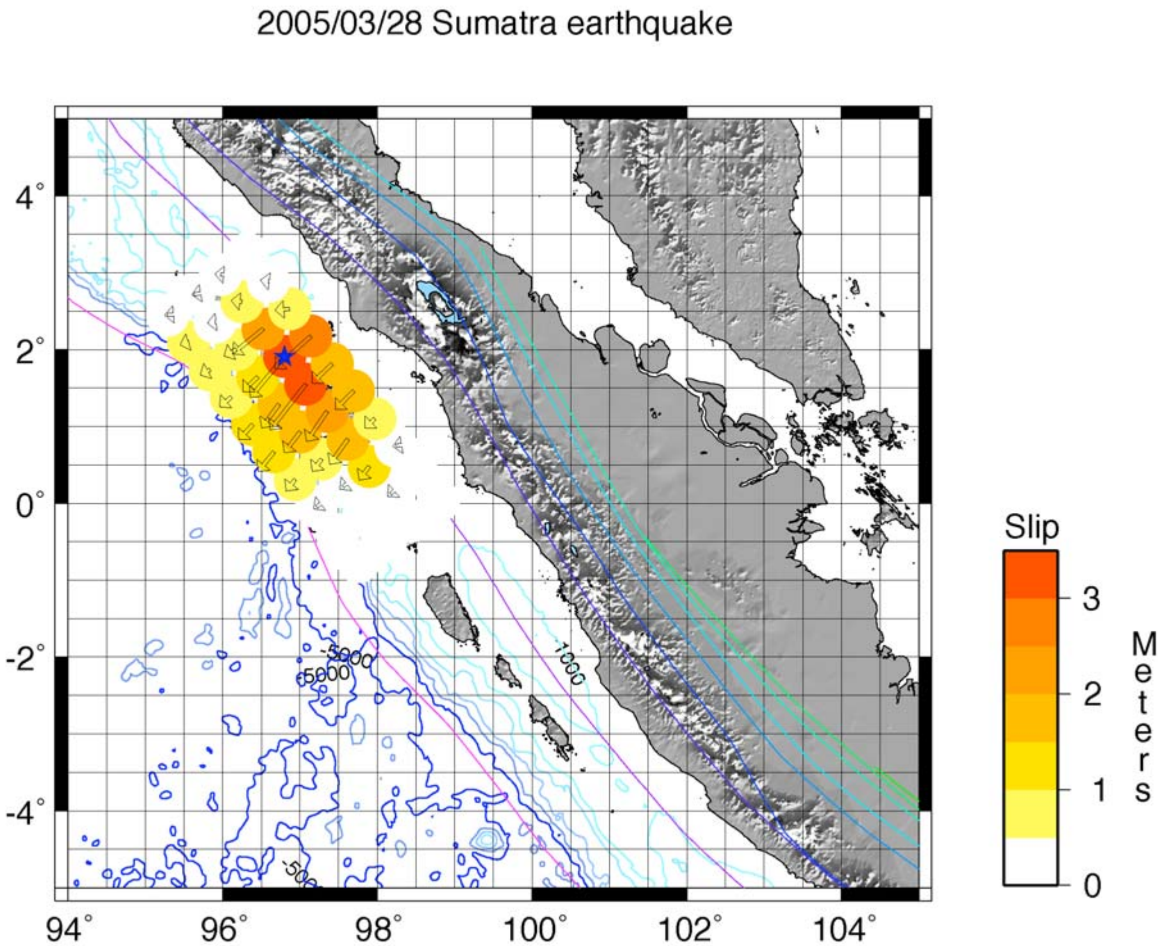

Figure 3. Rupture mode for the March 2005 Sumatra earthquake, south of the 2004 rupture zone.

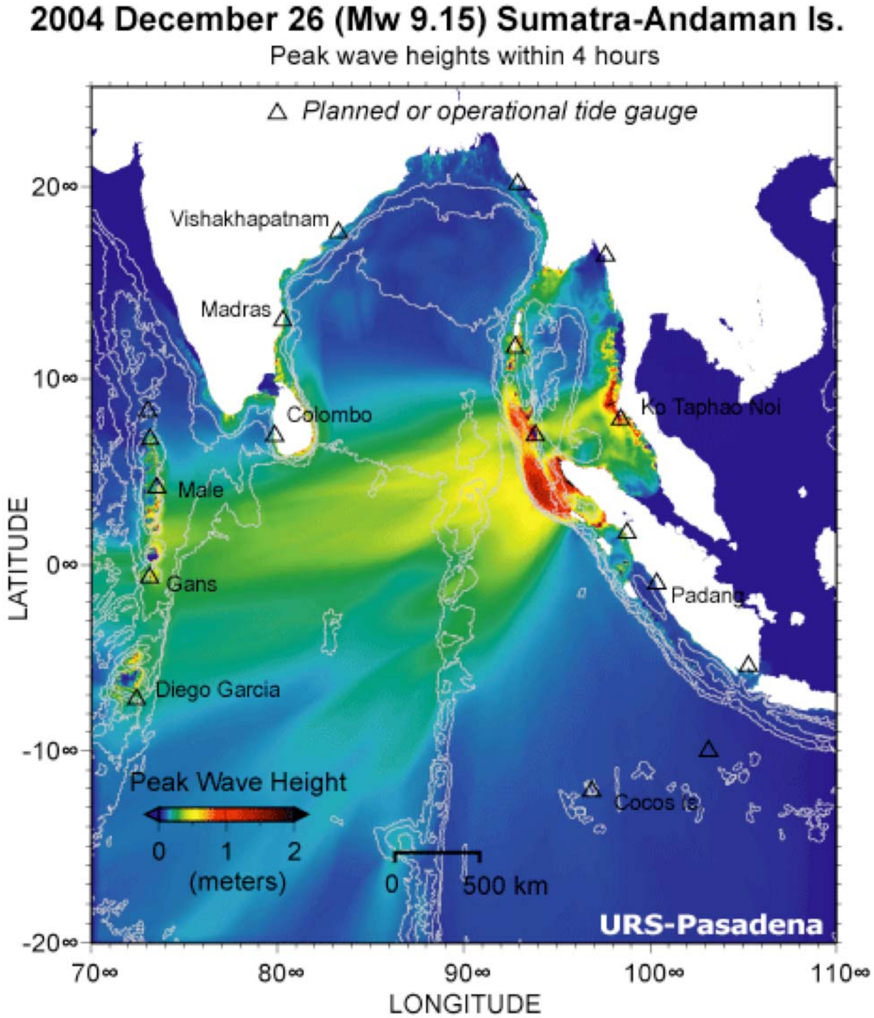

Figure 4. Tsunami waveheights based on our rupture model for the 2004 earthquake.

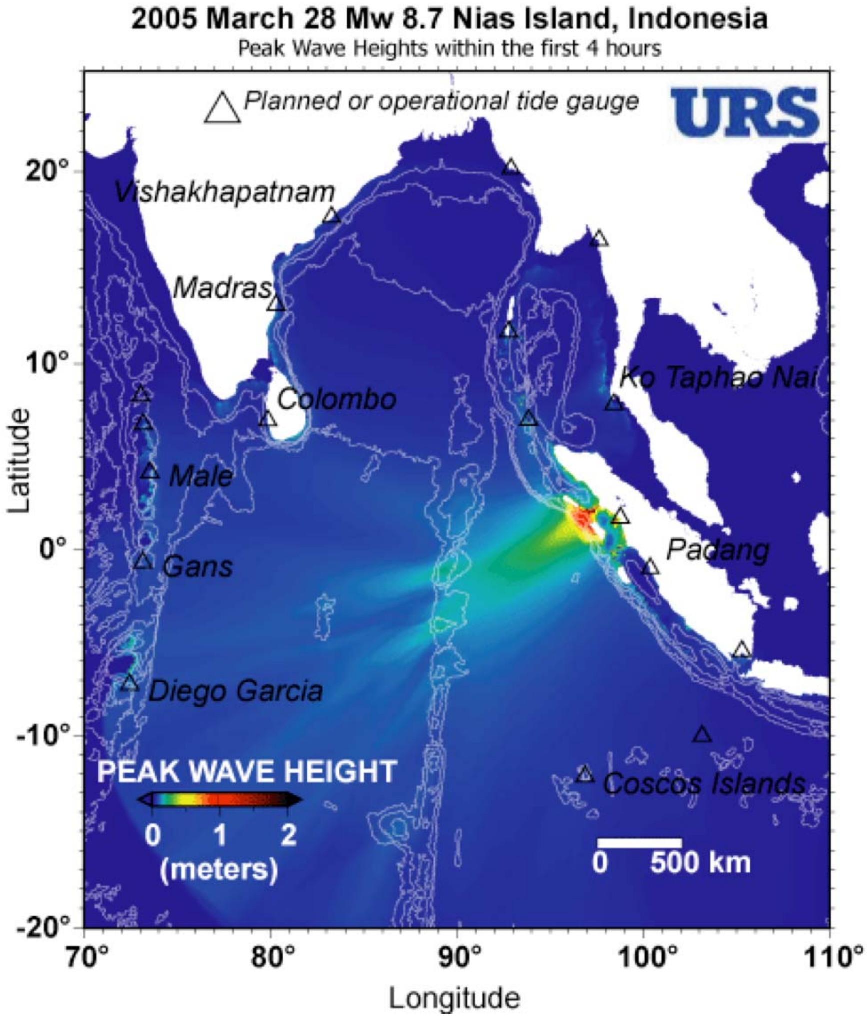

Figure 5. Tsunami waveheights for our 2005 rupture model.